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Remarks:
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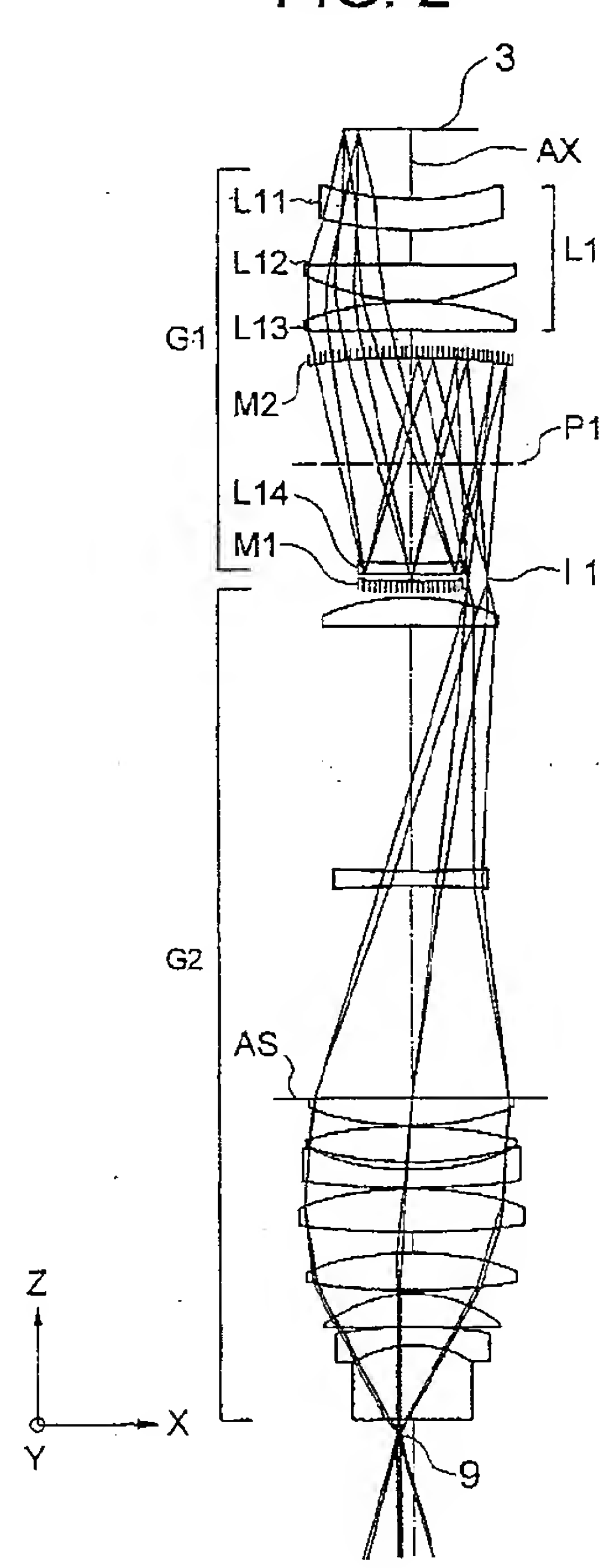
(54) Catadioptric optical system and exposure apparatus equipped with the same

(57) A catadloptric optical system comprising a first imaging optical system for forming an intermediate image of a first plane surface, a second imaging optical system for forming a final image of the first plane surface onto a second plane surface which is substantially parallel to the first plane surface, and a catadioptric type optical system disposed in the optical path from the first plane surface to the second plane surface and including a first reflecting surface which reflects light coming from through the first plane surface and a second reflecting surface for directing the light reflected by the first reflecting surface toward the second plane surface. At least one of the first and second reflecting surfaces Is a concave reflecting surface. All of the optical elements of the catadloptric optical system are disposed on a single linear optical axis.

FIG. 2



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Description

[0001] This application claims the benefit of Japanese Patent application No. 11-199467 which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a catadloptric optical system and a projection exposure apparatus equipped with the catadioptric optical system suitable when manufacturing in a photolithography process, for example, a semiconductor device or a liquid crystal display device. In particular, the invention relates to a catadioptric optical system suitable for a scanning type projection exposure apparatus.

Related Background Art

[0003] In a photolithography process for manufacturing semiconductor devices and the like, there is used a projection exposure apparatus by which a pattern image formed on a photomask or reticle (collectively referred to as "reticle" hereinafter) is projected and exposed onto a wafer, a glass plate, etc. coated with a photoresist or the like via a projection optical system. As the integration of the semiconductor devices and the like is improved, there has been a demand for a higher resolution of the projection optical system used in the projection exposure apparatus. In order to satisfy such a demand, there have been occurred necessities for shortening the wavelength of illumination light and increasing the numerical aperture (hereinafter referred to as "NA") of the projection optical system. In particular, regarding the exposure wavelength, replacing g-line (λ=436 nm), i-line (λ=356 nm) and, further, KrF excimer laser light (λ = 248 nm) are currently used. In the future, ArF excimer laser light (λ = 193 nm) and F_2 laser light (λ =157 nm) will probably be used.

[0004] However, as the wavelength of the illumination light becomes shorter, a fewer kinds of glass materials can be practically used due to light absorption. As a result, when the projection optical system is constructed by a refraction system alone, that is, only by optical elements not including a reflecting mirror with refractive power (a concave or convex mirror), chromatic aberration cannot be corrected. Additionally, because the optical performance required of the projection optical system is extremely high, various kinds of aberrations should preferably be corrected to a level of almost no aberration. Eighteen or more lens elements are required for correcting various aberrations to a desired optical performance by a refraction type projection optical system constituted of lens elements (see, for example, Japanese Unexamined Patent Publication Hei No. 5-173065), and it is difficult to suppress light absorption and avoid manufacturing costs' increase. Moreover, when extreme ultraviolet light with a wavelength of 200 nm or less is used, the optical perrormance may be affected by, for example, light absorption in glass material and on an anti-reflection film on the lens surface.

[0005] Further, although the oscillation bandwidth of laser light sources with an oscillation wavelength of 200 nm or less has been considerably narrowed, the bandwidth has still a certain wavelength width. Thus, to project and expose a pattern maintaining good contrast, correction of chromatic aberration of the order of pm (pico meter) is required. The optical system disclosed in the above-mentioned Japanese Unexamined Patent Publication Hei No. 5-173065 is a refraction type lens system made from a single kind of glass material, and its chromatic aberration is too large to be used with a light source having a wavelength width.

[0006] On the other hand, a reflection type optical system utilizing power (refractive power) of a concave mirror and the like does not effect chromatic aberration and, with respect to Petzval sum, creates a contribution with an opposite sign to a lens element. As a result, a so-called catadioptric optical system (hereinafter referred to as "catadioptric optical system"), which. combines a catoptric optical system and a dioptric optical system together, can correct chromatic aberration as well as other various aberrations to a level of almost no aberration without increasing the number of lenses. Thus, a catadioptric optical system is an optical system having at least one lens element and at least one reflecting mirror with refractive power.

[0007] However, when a concave mirror is incorporated on the optical axis of a projection optical system of a projection exposure apparatus, light from the reticle side incident on the concave mirror is reflected toward the reticle. Addressing this problem, techniques to separate the optical path of light incident on a concave mirror from the optical path of light reflected by the concave mirror and also to direct the reflected light from the concave mirror to the wafer direction, i.e., various techniques to implement a projection optical system by a catadioptric optical system, have been extensively proposed.

[0008] However, when using a beam splitter as is used in the optical system disclosed in Japanese Unexamined Patent Publication Hei No. 5-281469, it is difficult to secure large-sized glass material for manufacturing the optical system. In addition, in the case of the optical system disclosed in Japanese Unexamined Patent Publication Hei No.

5-51718, an optical path folding mirror (folding mirror) or a beam splitter is required, a plurality of lens barrels are required for manufacturing the optical system, resulting in such problems as difficulties in manufacture or in adjusting optical elements. A light beam impinges obliquely onto a plane reflecting mirror (folding mirror) for changing the optical path direction incorporated in a catadioptric optical system as necessary. Accordingly, extremely high surface accuracy of the mirror is required, resulting thus in the difficulty of the manufacture of the mirror.
Further, the mirror is easily affected by vibration.

[0009] Meanwhile, when an optical path separating method disclosed in U.S. Patent No. 5,717.518 is used, optical elements constituting a optical system can all be disposed along a single optical axis. As a result, the optical system can be manufactured with high accuracy following an optical element adjustment method conventionally used in the projection optical system manufacture. However, the system requires a central light-shielding portion to shield light beam propagating along the optical axis, resulting in the contrast deterioration of a pattern of a certain frequency.

[0010] Additionally, because it is difficult to provide an anti-reflection film with sufficient optical performance in the extreme ultraviolet wavelength region, it is also required that the number of optical elements constituting an optical system be reduced as much as possible.

[0011] As can be seen from the above, it is preferable that, to expose a pattern having a linewidth of 0.18 μm or less, an optical system in which a good chromatic aberration correction capability is realized even when using a light source with a wavelength of 200 nm or less such as ArF or F_2 laser, no central light-shielding is used, a high numerical aperture of NA 0.6 or more can be secured, and the number of refractive and reflecting components is reduced as much as possible be provided

SUMMARY OF THE INVENTION

[0012] The present invention has been made in view of the above problems, and the object of the invention is to provide a catadioptric optical system in which chromatic aberration is well corrected in the extreme ultraviolet wavelength region, in particular, even in the wavelength region of 200 nm or less, and a NA (0.6 or more) necessary for high resolution is secured, and the number of refractive and reflecting components is reduced as much as possible; a projection exposure apparatus equipped with the optical system.

[0013] To resolve the above problems, the present invention provides a catadioptric optical system, which comprises a first catadioptric type imaging optical system for forming an intermediate image of a first surface and a second refraction type imaging optical system for telecentically forming the final image of said first surface onto a second surface based on said light from said intermediate image;

wherein said first imaging optical system has a lens group including at least one positive lens element, a first reflecting surface which reflects light passed through said lens group, and a second reflecting surface for directing light reflected by said first reflecting surface to said second imaging optical system; at least one of said first and second reflecting surfaces is a concave reflecting surface; and said second imaging optical system has an aperture diaphragm;

wherein all of the optical elements of said catadioptric optical system are disposed on a single linear optical axis, and said first surface and said second surface are plane surfaces which are approximately mutually parallel; and

wherein an exit pupil of said catadioptric optical system is approximately circular. Here, the second reflecting surface has an aperture portion (hole) at an off-axis position for making light from the first surface pass or pass through in the direction of the first reflecting surface, and the first reflecting surface also has an aperture portion (hole) for making the light reflected by said second reflecting surface pass or pass through in the direction of the second imaging optical system.

[0014] That the exit pupil is substantially circular means that there is no shielding object in the neighborhood of the center of the optical axis.

[0015] Further, in the present invention, the following condition is preferably satisfied:

$$0.04<|fM1|/L<0.4$$

wherein fM1 is a focal length of said concave reflecting surface of said first or second reflecting surface, and L is a distance along the optical axis from said first surface to said second surface.

[0016] Further, in the present invention, the following condition is preferably satisfied:

$$0.6<|\beta M1|<20$$

wherein β M1 is a magnification of said concave reflecting surface of said first or second reflecting surface.

[0017] Further, in the present invention, the following condition is preferably satisfied:

$$0.3<|\beta 1|<1.8$$

wherein β1 is a magnification of said first imaging optical system.

[0018] Further, the present invention provides a projection exposure apparatus comprising:

an illumination optical system for illuminating a mask on which a predetermined pattern is formed; and
a catadioptric optical system according to any one of claims 1-7 or 10 to 14 for projecting said predetermined pattern of said mask disposed on said first surface onto a photosensitive substrate disposed on said second surface.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019]

FIG. 1 is a view schematically illustrating the configuration of a projection exposure apparatus equipped with a catadioptric projection optical system to which the present invention is applied.
FIG. 2 is a view illustrating a lens configuration of a catadioptric optical system in accordance with a first embodiment of the present invention.
FIG. 3 is a view showing transverse aberrations of the catadioptric optical system in accordance with the first embodiment.
FIG. 4 is a view illustrating a lens configuration of a catadioptric optical system in accordance with a second embodiment of the present invention.
FIG. 5 is a view showing transverse aberrations of the catadioptric optical system in accordance with the second embodiment.
FIG. 6 is a view illustrating a lens configuration of a catadioptric optical system in accordance with a third embodiment of the present invention.
FIG. 7 is a view showing transverse aberrations of the catadioptric optical system in accordance with the third embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] In the following, the catadioptric optical system in accordance with the present invention will be described with reference to the accompanying drawings. The system is a catadioptric optical system provided with a first catadioptric type imaging optical system G1 for forming an intermediate image I1 of a first surface 3 and with a second refraction type imaging optical system G2 for telecentrically forming the final image of the first surface 3 onto a second surface 9 (wafer surface, i.e., the final image plane) based on light from the intermediate image. The first optical system G1 has a lens group including at least one positive lens element, a first reflecting surface M1 which reflects light passed through the lens group and is substantially collimated, and a second reflecting surface M2 for directing light reflected by the first reflecting surface M1 to the second imaging optical system G2; and at least one of the first and second reflecting surfaces is a concave reflecting surface. Further, the second imaging optical system G2 has aperture diaphragm AS, all of the optical elements of the catadioptric optical system are disposed on a single linear optical axis AX, the first surface 3 and the second surface 9 are plane surfaces which are substantially mutually parallel; and an exit pupil of the catadioptric optical system is substantially circular. In the present invention, a structurally reasonable catadioptric optical system is achieved by making the effective projected area an annular shape and by preventing mutual interference of optical elements through appropriately positioning the first and second reflecting surfaces M1 end M2.

[0021] Further, in the present invention, the following condition is preferably satisfied:

$$(1) \qquad 0.04<|fM1|/L<0.4$$

wherein fM1 is a focal length of the concave reflecting surface of the first or second reflecting surface, and L is a distance along the optical axis AX from the first surface 3 to the second surface 9. The condition (1) defines an appropriate power range of the concave reflecting surface. In the present inventive optical system, positive Petzval sum created by refractive lenses is corrected by negative Petzval sum created by the concave mirror. When the power is over the upper limit value of the condition (1), the positive Petzval sum created by refractive lenses cannot be sufficiently corrected, and the flatness of the image deteriorates. In contrast, when the power is below the lower limit value of the

condition (1), the Petzval sum is overcorrected, and the flatness of the image deteriorates similarly

[0022] Further, in the present invention, the following condition is preferably satisfied:

$$(2) \qquad 0.6<|\beta M1|<20$$

wherein $\beta M1$ represents a magnification of the concave reflecting surface of the first or second reflecting surface. The condition (2) defines an appropriate magnification range of the concave reflecting mirror. When the magnification is over the upper limit value of the condition (2) or is below the lower limit value of the condition (2), symmetricity of the first imaging system G1 is seriously affected, large coma aberration being produced, and causes the image deterioration.

[0023] Further, in the present invention, the following condition is preferably satisfied:

$$(3) \qquad 0.3<|\beta 1|<1.8$$

wherein $\beta 1$ is a magnification of the first imaging optical system G1. The condition (3) defines an appropriate magnification range of the first imaging optical system G1. When the magnification is over the upper limit value of the condition (3) or is below the lower limit value of the condition (3), power balance collapses, causing distortion aberration (distortion) and coma aberration, and the imaging performance deteriorates.

[0024] Further, in the present invention, it is preferable that, the first imaging optical system G1 has a light beam which intersects at least three times a plane P1 perpendicular to the optical axis AX. Light from the first surface 3, after being refracted by the lens group L1, passes through the plane P1 (the first time) to the reflecting surface M1, and, after being reflected by the surface, passes through again the plane P1 (the second time) to the reflecting surface M2. Further, the light, after being reflected by the reflecting surface M2, passes through again the plane P1 (the third time) and forms the intermediate image I1. In addition, by having made the effective projected area an annular shape, the light and the optical elements such as the reflecting surfaces M1 and M2 can be positioned so as not to physically interfere with each other.

[0025] Further. as mentioned above, the catadioptric optical system of the present invention is telecentric on the second surface 9 side (wafer surface side), but it is preferable that the optical system be additionally telecentric on the first surface 3 side (reticle surface side).

[0026] In the following, embodiments of the present invention will be described with reference to the attached drawings. FIG. 1 is a drawing schematically illustrating the overall configuration of a projection exposure apparatus equipped with a projection optical system in accordance with any embodiment of the present invention optical systems. Note that, in FIG. 1. a Z-axis is set parallel to the optical axis AX of the projection optical system 8 constituting the projection exposure optical system, an X-axis is set parallel to the plane of the drawing of FIG.1, and a Y-axis is set perpendicular to the plane of the drawing, both of X- and Y- axes being in a plane perpendicular to the optical axis AX. Further, a reticle 3, as a projection original plate, on which a predetermined circuit pattern is formed is disposed on the object plane of the projection optical system 8, and a wafer 9, as a substrate, coated with a photoresist is disposed on the image plane of the projection optical system 8.

[0027] Light emitted from light source 1, via the illumination optical system 2, uniformly illuminates the reticle on which the predetermined pattern is formed. One or more folding mirrors for changing the optical path direction are disposed, as required, on the optical path from the light source 1 to the illumination optical system 2.

[0028] Note further that the illumination optical system 2 comprises optical systems such as an optical integrator constituted of, for example, a flyeye lens or an internal reflection type integrator for forming a plane light source having a predetermined size and shape; a variable field stop (reticle blind) for defining the size and shape of an illumination area on the reticle 3; and a field stop imaging optical system for projecting the image of this field stop on the reticle. Also note that, as an optical system from the light source 1 to the field stop, the illumination optical system disclosed in U.S. Patent No. 5,345,292 may be applied.

[0029] The reticle 3 is, via reticle holder 4, held on reticle stage 5 parallel to the XY plane. On the reticle 3 is formed a pattern to be transferred, and the overall pattern area is illuminated with light from the illumination optical system 2. The reticle stage 5 is so configured that the stage is two-dimensionally movable along a reticle plane (i.e., the XY plane) by the effect of a drive system, not shown, and that the coordinate position of the stage is measured by interferometer 7 using reticle moving mirror 6 and is position-controlled.

[0030] Light from the pattern formed on the reticle 3 forms , via the projection optical system 8, a mask pattern image onto the wafer which is a photosensitive substrate. The projection optical system 8 has a variable aperture diaphragm AS (see FIG. 2) near its pupil and is substantially telecentric on both of the reticle 3 and wafer 9 sides.

[0031] The wafer 9 is, via a wafer holder 10, held on a wafer stage 11 parallel to the XY plane. Onto a substantially

similar exposure area to the illuminated area on the reticle 3 is thus formed the pattern image.

[0032] The wafer stage 11 is so configured that the stage is two-dimensionally movable along a wafer plane (i.e., the XY plane) by the effect of a drive system, not shown, and that the coordinate position of the stage is measured by interferometer 13 using wafer moving mirror 12 and thus the wafer stage is position-controlled.

[0033] As described above, the field view area on the mask 3 (illumination area) and the projection area (exposure area) on the wafer 9 both defined by the projection optical system 8 are rectangle-shaped areas having a short-side along the X-axis. Aligning the mask 3 and the wafer 9 is thus performed by using the drive systems and the interferometers (7, 13), and the wafer 9 is positioned onto the image plane of the projection optical system by the use of an autofocus/autoleveling system, not shown. Further, by synchronously moving (scanning) the mask stage 5 and the wafer stage 11, and accordingly, the mask 3 and the wafer 9, along the short-side direction of the rectangle-shaped exposure and illumination areas, i.e., along the X-direction, the mask pattern is scanningly exposed onto an area on the wafer 9 of which width is equal to the long-side length of the exposure area and of which length is equal to the scanning (moving) length of the wafer 9.

[0034] Note that over the overall optical path between the light source 1 and the wafer 9 is formed an inert gas atmosphere such as nitrogen or helium gas into which the exposure light is little absorbed.

(First Embodiment)

[0035] FIG. 2 is a drawing illustrating a lens configuration of a catadioptric optical system in accordance with a first embodiment of the present invention. The system is a catadioptric optical system comprising a first catadioptric type imaging optical system G1 for forming an intermediate image I1 of a reticle (first surface) 3 and a second refraction type imaging optical system G2 for telecentrically forming the final image of the reticle surface 3 onto a wafer (second surface) 9 based on light from the intermediate image I1.

[0036] The first imaging optical system G1 has a lens group L1 including at least one positive lens element, a first reflecting surface M1 which reflects light passed through the lens group L1, and a second reflecting surface M2 for directing light reflected by the first reflecting surface M1 to the second imaging optical system G2, at least one of the first and second reflecting surfaces being a concave reflecting surface, and the second imaging optical system G2 having an aperture diaphragm AS. Further. all of the optical elements of the catadioptric optical system are disposed on a single linear optical axis AX, the reticle surface 3 and the wafer surface 9 are plane surfaces which are substantially mutually parallel; and an exit pupil of the catadioptric optical system is substantially circular.

[0037] In Table 1 are listed values of items of the projection optical system in accordance with the first embodiment. In Table 1, numerals in the leftmost column represent the order of lens surfaces from the reticle 3 (first object plane) side, r is the radius of curvature of the lens surface, d is the lens surface interval from the lens surface to the next lens surface, β is the overall magnification of the catadioptric optical system, NA is the numerical aperture on the wafer side (the second surface side), and λ is the standard wavelength. Note that the refractive indexes of the glass used in the first embodiment equal to those in the second embodiment.

[0038] Further, ASP in the lens data represents an aspherical surface. In each embodiment, an aspherical surface can be expressed by the following mathematical formula:

$$Z = (y^2/r) /[1 + \{1 - (1 + \kappa) \cdot y^2/r^2\}^{1/2}] + A \cdot y^4 + B \cdot y^6 + C \cdot y^8 + D \cdot y^{10} + E \cdot y^{12} + F \cdot y^{14}$$

wherein y is the height in the direction normal to the optical axis, Z is a displacement amount (sag amount) from the tangential plane at the apex of the aspherical surface to a position of the aspherical surface at the height y measured along the direction of the optical axis, r is the radius of curvature at the apex, κ is a conical coefficient, and A-F are aspherical coefficients of the n-th order.

[0039] Note that, in all of the values of items of the following embodiments, similar reference codes to those of this embodiment are used. Here, as an example of the unit for the radius of curvature r and the lens surface interval d in the values of items of all embodiments, mm may be used.

[Table 1]

I β I = 1/4
NA=0.7 5
λ = 193. 3nm

[Table 1] (continued)

$\mid\beta\mid = 1/4$			
No.	r	d	Glass Material
1:	-211.97583	30.000000	SiO2
2:	-354.80161	35.347349	
3:	-8888.21083	38.000000	SiO2
4:	-227.79960	0.944905	
5:	303.84978	27.415767	SiO2
ASP:			
κ=0.000000			
A=+0.743561$\times 10^{-8}$ B=-0.230589$\times 10^{-12}$			
C=-0.115168$\times 10^{-17}$ D=-0.753145$\times 10^{-22}$			
6:	237634.15996	30.000000	
7:	∞ (Plane)	214.776416	
8:	-348.87932	12.000000	SiO2
9:	4267.07121	5.579827	
10:	-362.24910	-5.579827	(Reflecting surface)
ASP:			
κ=3.260270			
A=+0.859110$\times 10^{-8}$ B=+0.351935$\times 10^{-12}$			
C=-0.100064$\times 10^{-15}$ D=+0.318170$\times 10^{-19}$			
E=-0.489883$\times 10^{-23}$			
11:	4267.07087	-12.000000	SiO2
12:	-348.87932	-214.776416	
13:	642.80918	246.776416	(Reflecting surface)
ASP:			
κ=1.840470			
A=0.198825$\times 10^{-8}$ B=0.556479$\times 10^{-13}$			
C=0.597091$\times 10^{-18}$ D=0.492729$\times 10^{-22}$			
E=-0.103460$\times 10^{-26}$			
14:	208.71115	33.000000	SiO2
15:	-2529.7293.0	257.546203	
16:	-1810.41832	14.500000	SiO2
ASP:			
κ=0.000000			
A=-0.885983$\times 10^{-7}$ B=-0.200044$\times 10^{-11}$			
C=-0.570861$\times 10^{-16}$ D=+0.456578$\times 10^{-22}$			
E=-0.493085$\times 10^{-25}$			
17:	851.98207	220.408225	
18:	15200.59096	30.000000	SiO2
19:	-268.76515	0.200000	
20:	434.96005	36.013163	CaF2
ASP:			
κ=0.000000			

[Table 1] (continued)

$\lvert\beta\rvert = 1/4$			
No.	r	d	Glass Material
$A=-0.161380\times10^{-7}$ $B=+0.153066\times10^{-12}$			
$C=+0.108604\times10^{-17}$ $D=+0.319975\times10^{-21}$			
$E=-0.101080\times10^{-25}$			
21:	-345.83883	10.489902	
22:	-215.91874	20.000000	SiO2
23:	-619.95152	0.200000	
24:	415.08345	40.000000	SiO2
25:	-1275.90912	26.288090	
26:	324.91386	35.000000	SiO2
27:	-740.00769	5.214992	
ASP:			
$\kappa=0.000000$			
$A=+0.138330\times10^{-7}$ $B=+0.194125\times10^{-12}$			
$C=-0.258860\times10^{-13}$ $D=-0.196062\times10^{-22}$			
$E=+0.363539\times10^{-26}$			
28:	140.91060	34.000000	SiO2
29:	1406.88948	0.500000	
30:	355.40083	17.506069	SiO2
31:	98.27403	1.561573	
32:	105.27944	75.940555	SiO2
33:	1597.37798	12.920542	

(Refractive index of glass material)

[0040]

	λ=193.3nm+0.48pm	λ=193.3nm	λ=193.3nm-0.48pm
SiO2	1.56032536	1.5603261	1.56032685
CaF2	1.50145434	1.5014548	1.50145526

(Condition correspondence value)

[0041]

(1) $\lvert fM1\rvert = 181.1246/1350=0.13417$
(2) $\lvert \beta M1\rvert = \lvert-1.21007\rvert=1.21007$
(3) $\lvert \beta 1\rvert = \lvert-1.1454\rvert=1.1454$

[0042] FIG. 3 shows transverse aberrations (coma aberrations) of the catadioptric optical system in accordance with the embodiment in the meridional (tangential) and sagittal directions. In each diagram, Y indicates the image height, continuous line indicates the standard wavelength (λ =193.3nm), dotted line indicates λ =193.3nm+0.48pm, and alternate long and short line indicates λ =193.3nm-0.48pm (the same is applied in the second embodiment). Note that, in all of the various aberration diagrams of the following embodiments, similar reference codes to those of this embodiment are used. As can be clearly seen from the aberration diagrams, aberrations are well-balancedly corrected in the overall exposure area in the catadioptric optical system of this embodiment in spite of the both-sides telecentricity along with the imaging performance deterioration due to the light absorption by the applied glass materials being prevented.

(Second Embodiment)

[0043] FIG. 4 is a drawing illustrating a lens configuration of a catadioptric optical system in accordance with a second embodiment. The system is a catadioptric optical system comprising a first. catadioptric type imaging optical system G1 for forming an intermediate image I1 of a reticle (first surface) 3 and a second refraction type imaging optical system G2 for telecentrically forming the final image of the reticle surface 3 onto a wafer (second surface) 9 based on light from the intermediate image I1.

[0044] The first imaging optical system G1 has a lens group L1 including at least one positive lens element, a first reflecting surface M1 which reflects light passed through the lens group L1, and a second reflecting surface M2 for directing light reflected by the first reflecting surface M1 to the second imaging optical system G2; at least one of the first and second reflecting surfaces is a concave reflecting surface; and the second imaging optical system G2 has an aperture diaphragm AS. Further, all of the optical elements of the catadioptric optical system are disposed on a single linear optical axis AX, the reticle surface 3 and the wafer surface 9 are plane surfaces which are substantially mutually parallel; and an exit pupil of the catadioptric optical system is substantially circular.

[0045] In Table 2 are listed values of items of the projection optical system in accordance with the second embodiment. Note that reference codes in Table 2 are similarly defined as those in FIG. 1, aspherical surface ASP can be expressed by the above-described mathematical formula.

[Table 2]

$\|\beta\| = 1/6$			
NA = 0. 75 λ = 193. 3 nm			
No.	r	d	Glass Material
1:	521.54601	23.000000	SiO2
2:	-191794.5079	0.944905	
3:	194.28987	30.000000	SiO2
ASP: κ=0.000000 A=-0.155326×10^{-8} B=-0.140791×10^{-12} C=$+0.176234\times10^{-17}$ D=-0.155625×10^{-21}			
4:	452.66236	300.000000	
5:	-589.38426	12.000000	SiO2
6:	1106.79674	5.000000	
7:	-482.64964	-5.000000	(Reflecting surface)
ASP: κ=7.430564 A=$+0.199000\times10^{-8}$ B=-0.957889×10^{-12} C=-0.122172×10^{-15} D=$+0.305937\times10^{-19}$ E=-0.126279×10^{-22}			
8:	1106.79671	-12.000000	SiO2
9:	-589.38426	-273.707398	
10:	455.39924	477.535323	(Reflecting surface)
ASP: κ=0.000000 A=$+0.434199\times10^{-9}$ B=$+0.327908\times10^{-14}$ C=$+0.360429\times10^{-19}$ D=-0.622589×10^{-24}			
> 11:	300.69546	29.000000	SiO2
12:	-3836.44237	191.527911	

[Table 2] (continued)

$\lvert \beta \rvert = 1/6$			
No.	r	d	Glass Material
13:	-4996.75666	15.000000	SiO2
ASP:			
κ=0.000000			
A=-0.601871E-07 B=-0.111865×10^{-11}			
C=-0.177478×10^{-16} D=$+0.104425\times10^{-23}$			
E=-0.236872×10^{-25}			
14:	1631.22452	164.229823	
15:	761.43970	32.000000	SiO2
16:	-416.24467	7.787594	
17:	385.90210	43.198650	CaF2
ASP:			
κ=0.000000			
A=-0.127289×10^{-7} B=$+0.112712\times10^{-12}$			
C=-0.237720×10^{-18} D=$+0.283035\times10^{-21}$			
E=-0.177785×10^{-25}			
18:	-325.55463	16.575364	
19:	-220.30976	20.000000	SiO2
20:	-755.61144	9.063759	
21:	359.10784	37.871908	SiO2
22:	-1575.91947	1.464560	
23:	235.63612	32.000000	SiO2
24:	-2200.62013	1.000000	
ASP:			
κ=0.000000			
A=$+0.198616\times10^{-7}$ B=-0.109623×10^{-12}			
C=0.106669×10^{-16} D=-0.466071×10^{-21}			
E=$+0.853932\times10^{-26}$			
25:	159.89570	33.600000	SiO2
26:	2158.79385	0.000000	
27:	406.09986	9.500000	SiO2
28:	68.76384	4.196119	
29:	70.58705	75.473363	SiO2
30:	2340.17874	9.379567	

(Condition correspondence value)

[0046]

(1) $\lvert fM1 \rvert = 241.3248/1339.26 = 0.18019$
(2) $\lvert \beta M1 \rvert = \lvert -12.51 \rvert = 12.51$
(3) $\lvert \beta 1 \rvert = \lvert -0.6135 \rvert = 0.6135$

[0047] FIG. 5 shows transverse aberration diagrams of the catadioptric optical system in accordance with the second embodiment. As can be clearly seen also from the aberration diagrams, aberrations are well-balancedly corrected in the overall exposure area.

(Third Embodiment)

[0048] FIG. 6 is a drawing illustrating a lens configuration of a catadioptric optical system in accordance with a third embodiment. The system is a catadioptric optical system comprising a first catadioptric type imaging optical system G1 for forming an intermediate image I1 of a reticle (first surface) 3 and a second refraction type imaging optical system G2 for telecentrically forming the final image of the reticle surface 3 onto a wafer (second surface) 9 based on light from the intermediate image I1.

[0049] The first imaging optical system G1 has a lens group L1 including at least one positive lens element, a first reflecting surface M1 which reflects light passed through the lens group L1, and a second reflecting surface M2 for directing light reflected by the first reflecting surface M1 to the second imaging optical system G2; at least one of the first and second reflecting surfaces is a concave reflecting surface; and the second imaging optical system G2 has an aperture diaphragm AS. Further, all of the optical elements of the catadioptric optical system are disposed on a single linear optical axis AX, the reticle surface 3 and the wafer surface 9 are plane surfaces which are substantially mutually parallel; and an exit pupil of the catadioptric optical system is substantially circular.

[0050] In Table 3 are listed values of items of the projection optical system in accordance with the third embodiment. Note that reference codes in Table 3 are similarly defined as those in FIG. 1, aspherical surface ASP can be expressed by the above-described mathematical formula.

[Table 3]

$\vert\beta\vert = 1/4$			
NA=0.75			
λ = 157. 6 nm			
No.	r	d	Glass Material
1:	314.69351	28.000000	CaF2
2:	-934.65900	37.000000	
ASP:			
κ=0.000000			
$A=-0.229218\times10^{-7}$ $B=\div0.947150\times10^{-12}$			
$C=-0.128922\times10^{-16}$ $D=-0.190103\times10^{-20}$			
$E=-0.386976\times10^{-25}$			
3:	-639.17871	23.000000	CaF2
ASP:			
κ =0.000000			
$A=-0.108326\times10^{-7}$ $B=+0.924937\times10^{-12}$			
$C=-0.326453\times10^{-16}$ $D=-0.342966\times10^{-20}$			
$E=+0.132323\times10^{-25}$			
4:	-318.93314	245.763430	
5:	-108.60441	10.000000	CaF2
ASP:			
κ=0.495309			
$A=0.486675\times10^{-7}$ $B=0.492347\times10^{-11}$			
$C=-0.606490\times10^{-16}$ $D=0.180500\times10^{-18}$			
$E=-0.766603\times10^{-23}$ $F=0.138880\times10^{-26}$			
6:	-2160.76276	14.249561	
7:	-165.34978	-14.249561	(Reflecting surface)
ASP:			
κ=1.132286			

[Table 3] (continued)

| β | = 1/4			
No.	r	d	Glass Material
$A=+0.201000\times10^{-7}$ $B=+0.102160\times10^{-11}$			
$C=-0.209696\times10^{-16}$ $D=+0.126536\times10^{-19}$			
$E=+0.429651\times10^{-24}$ $F=-0.160033\times10^{-29}$			
8:	-2160.76276	-10.000000	CaF2
9:	-108.60441	-245.763430	
ASP:			
$\kappa=0.495309$			
$A=+0.486675\times10^{-7}$ $B=+0.492347\times10^{-11}$			
$C=-0.606490\times10^{-16}$ $D=+0.180500\times10^{-18}$			
$E=-0.766603\times10^{-23}$ $F=+0.138880\times10^{-26}$			
10:	-318.93314	-23.000000	CaF2
11:	-639.17869	-4.391997	
ASP:			
$\kappa=0.000000$			
$A=-0.108326\times10^{-7}$ $B=+0.924936\times10^{-12}$			
$C=-0.326453\times10^{-16}$ $D=-0.342966\times10^{-20}$			
$E=+0.132323\times10^{-25}$			
12:	-1183.44883	4.391997 (Reflecting surface)	
ASP:			
$\kappa=0.000000$			
$A=-0.183262\times10^{-10}$ $B=-0.246349\times10^{-12}$			
$C=+0.147599\times10^{-16}$ $D=+0.182045\times10^{-20}$			
$E=-0.115790\times10^{-25}$			
13:	-639.17869	23.000000	CaF2
ASP:			
$\kappa=0.000000$			
$A=-0.108326\times10^{-7}$ $B=+0.924936\times10^{-12}$			
$C=-0.326453\times10^{-16}$ $D=-0.342966\times10^{-20}$			
$E=+0.132323\times10^{-25}$			
14:	-318.93314	300.763420	
15:	756.86009	41.000000	CaF2
16:	-412.30872	15.942705	
ASP :			
$\kappa=0.000000$			
$A=+0.361860\times10^{-8}$ $B=+0.893121\times10^{-14}$			
$C=+0.135118\times10^{-18}$ $D=-0.735265\times10^{-23}$			
$E=+0.151108\times10^{-27}$			
17:	382.45831	36.000000	CaF2
18:	2411.92028	120.195566	

[Table 3] (continued)

| β | = 1/4			
No.	r	d	Glass Material
19:	203.57233	23.670903	CaF2
ASP:			
κ=0,000000			
$A=-0.666118\times10^{-8}$ $B=-0.225767\times10^{-12}$			
$C=-0.790187\times10^{-19}$ $D=-0.460596\times10^{-21}$			
$E=0.210563\times10^{-25}$ $F=-0.570908\times10^{-30}$			
20:	174.15615	417.834922	
21:	164.52297	20.000000	CaF2
ASP:			
κ=0.000000			
$A=+0.153241\times10^{-7}$ $B=+0.610531\times10^{-12}$			
$C=+0.252256\times10^{-15}$ $D=-0.150451\times10^{-20}$			
$E=+0.326670\times10^{-23}$ $F=-0.132886\times10^{-27}$			
22:	746.82563	20.284156	
23:	93.58470	23.000000	CaF2
ASP:			
κ=0.000000			
$A=-0.267761\times10^{-7}$ $B=+0.970828\times10^{-12}$			
$C=+0.117557\times10^{-15}$ $D=+0.718106\times10^{-19}$			
$E=-0.162733\times10^{-22}$ $F=+0.586684\times10^{-26}$			
24:	256.99945	21.338588	
25:	-129.21983	16.000000	CaF2
ASP:			
κ=0.000000			
$A=-0.588690\times10^{-8}$ $B=0.461959\times10^{-12}$			
$C=0.130813\times10^{-14}$ $D=-0.849445\times10^{-19}$			
$E=-0.123125\times10^{-22}$ $F=+0.290566\times10^{-26}$			
26:	-219.48522	1.000000	
27:	102.75126	19.500000	CaF2
ASP:			
κ=0.000000			
$A=-0.862905\times10^{-7}$ $B=-0.119006\times10^{-10}$			
$C=-0.124879\times10^{-14}$ $D=-0.367913\times10^{-18}$			
$E=-0.451018\times10^{-22}$ $F=+0.119726\times10^{-26}$			
28:	593.36680	1.000000	
29:	83.17946	18.815833	CaF2
ASP:			
κ=0.111409			
$A=-0.393239\times10^{-7}$ $B=-0.723984\times10^{-11}$			

[Table 3] (continued)

$\vert\beta\vert = 1/4$			
No.	r	d	Glass Material
	$C=-0.679503\times10^{-14}$ $D=-0.115217\times10^{-17}$		
	$E=-0.763652\times10^{-22}$ $F=+0.381047\times10^{-25}$		
30:	197.09247	1.000000	
31:	110.23581	43.599536	CaF2
	ASP:		
	$\kappa=0.000000$		
	$A=+0.850436\times10^{-9}$ $B=+0.126341\times10^{-10}$		
	$C=+0.168625\times10^{-13}$ $D=+0.782396\times10^{-17}$		
	$E=-0.233726\times10^{-20}$ $F=+0.333624\times10^{-24}$		
32:	∞ (Plane)	9.100000	

(Refractive index of glass material)

λ=157.6nm+1.29pm	157.6nm	157.6nm-1.29pm
CaF2 1.55999383	1.56	1.56000617

(Condition correspondence value)

[0051]

(1) $\vert fM1 \vert =82.6749/1350=0.06124$
(2) $\vert \beta M1 \vert = \vert -0.96128\vert =0.96128$
(3) $\vert \beta 1 \vert =\vert -1.4453\vert =1.4453$

[0052] FIG. 6 shows transverse aberration diagrams of the catadioptric optical system in accordance with the third embodiment. In each diagram, Y indicates the image height, continuous line indicates the standard wavelength (λ =157.6nm), dotted line indicates λ=157.6nm+1.29pm, and alternate long and short line indicates λ=157.6nm-1.29pm. As can be clearly seen also from the aberration diagrams, aberrations are well-balancedly corrected in the overall exposure area.

[0053] Meanwhile, the above-mentioned embodiments are applied to a scanning type projection exposure apparatus using a step-and-scan method (scanning method) in which a mask and a wafer are synchronously scanned with the speed ratio equal to the exposure magnification β while each shot area on a wafer is exposed using an exposure area of circular arc shape (a shape partially cut out of an annular shape). However, when the exposure field is, for example, about 5mmX5mm square, the above-mentioned embodiments can be applied also to a step-and-repeat type (one-shot type) projection exposure apparatus in which, after the mask pattern image being transferred onto one shot area on a wafer at one shot, a process wherein the mask pattern image is exposed onto a next shot area by two-dimensionally moving the wafer repetitively is repeated. It is to be noted that because, in the step-and-scan method, good imaging performance is required only within a slit-like exposure area (a shape extending in a predetermined direction, for example, a long rectangle, a trapezoid, a long hexagon, a circular arc, etc.), a larger shot area on a wafer can be exposed without large-sizing the projection optical system.

[0054] Meanwhile, in the above-mentioned embodiments, the invention is applied to a projection exposure apparatus used for the manufacture of semiconductor devices.
However, in addition to a projection exposure apparatus used for manufacture of semiconductor devices, the invention can be applied to, for example, an exposure apparatus transferring a display pattern onto a glass plate used for the manufacture of display devices including liquid crystal display devices, to an exposure apparatus transferring a display pattern onto a ceramics wafer used for the manufacture of thin film magnetic heads, to an exposure apparatus used for the manufacture of image pick-up devices (CCD, etc.). Also, the invention can be applied to an exposure apparatus transferring a circuit pattern onto a glass substrate or a silicon wafer used for the manufacture of a reticle or a mask.

[0055] The present invention is not limited to the above-mentioned embodiments, and it is obvious that the invention may be varied in many configurations without departing from the spirit and scope of the invention.

[0056] Further, the present invention can be configured as the following (A) or (B) configuration.

(A) A catadioptric optical system according to any one of claims 1-7 and 10 to 14, wherein all of the refractive elements constituting said catadioptric optical system are made from a single kind of glass material or from a plurality of glass materials including fluorite.

(B) A projection exposure apparatus comprising:

an illumination optical system for illuminating a mask on which a predetermined pattern is formed; and
a catadioptric optical system according to any one of claims 1-7 and 10 to 14 or to the above (A) for projecting said predetermined pattern of said mask disposed on said first surface onto a photosensitive substrate disposed on said second surface;

wherein said illumination optical system provides light of a wavelength of 250 nm or less.

[0057] As described above, the present invention can provide a catadioptric optical system in which chromatic aberration is well corrected in the extreme ultraviolet wavelength region, in particular, even in the wavelength region of 200 nm or less, and a NA (0.6 or more) necessary for high resolution is secured, and the number of refractive and reflecting components is reduced as much as possible. Further, exposure light can be effectively used since light absorption is little because of the small number of reflecting elements and the like. Still further, the projection exposure apparatus of the present Invention, being equipped with the above-mentioned catadioptric optical system, has an advantage that fine mask patterns can be accurately transferred.

Claims

1. A catadioptric optical system for forming an intermediate image of a first surface within the catadioptric optical system and for forming a final image of the first surface onto a second surface, comprising:

an optical axis:

an aperture stop which is arranged in an optical path between the intermediate image and the second surface;
a plurality of mirrors which are arranged on the optical axis; and
a plurality of lens elements which are arranged on the optical axis;

wherein at least two mirrors of the plurality of mirrors are arranged in an optical path between the first surface and the intermediate image, and
wherein at least one lens element of the plurality of lens elements are arranged in an optical path between the aperture stop and the second surface.

2. A catadioptric optical system according to claim 1, wherein the at least one lens element of the plurality of lens elements is arranged in an optical path between the first surface and the at least two mirrors.

3. A catadioptric optical system according to claim 2, wherein the lens element arranged in the optical path between the first surface and the at least two mirrors has a positive refractive power.

4. A catadioptric optical system according to any one of claims 1-3, wherein the at least two mirrors include at least one concave mirror.

5. A catadioptric optical system according to any one of claims 1-4, wherein the first surface and the second surface are substantially parallel to each other.

6. A catadioptirc optical system according to any one of claims 1-5, further comprising an exit pupil free from central light-shielding.

7. A catadioptric optical system according to any one of claims 1-6, wherein the catadioptric optical system forms the final image of the first surface at off-axis position on the second surface based on the light from an off-axis position on the first surface.

8. A catadioptric optical system according to any one of claims 1-7, wherein at least one lens element of the plurality of lens elements is arranged in an optical path between the at least two mirrors.

9. A catadioptric optical system according to any one of claims 1-8, wherein all the mirrors of the catadioptric optical system are arranged in an optical path between the first surface and the aperture stop.

10. A catadioptric optical system according to claim 9, wherein all the mirrors of the catadioptric optical system are arranged in an optical path between the first surface and the intermediate image.

11. A catadioptric optical system according to any one of claims 1-10, further comprising a plane perpendicular to the optical axis, wherein a light intersects the plane at least three times.

12. A catadioptric optical system according to any one of claims 1-11, wherein the catadioptric optical system is a bi-telecentric optical system.

13. A catadioptric optical system according to any one of claims 1-12, wherein the plurality of mirrors are even number.

14. A catadioptric optical system according to any one of claims 1-13, wherein the catadioptric optical system is devoid of planar folding mirrors.

15. A catadioptric optical system according to any one of claims 1-14, at least one lens element of the plurality of lens elements are arranged near the intermediate image.

16. A catadioptric optical system according to any one of claims 1-15, wherein the plurality of lens elements comprise a lens element made of CaF_2

17. A catadioptric optical system according to claim 16, wherein the lens element made of CaF_2 is arranged in an optical path between the aperture stop and the second surface.

18. A catadioptric optical system according to any one of claims 1-16, wherein the all of the plurality of lens elements are made of same material.

19. A catadioptric optical system according to any one of claims 1-18, further comprising at least one aspherical surface.

20. A catadiotric optical system according to claim 19, wherein the at least one aspherical surface comprises an aspherical lens surface.

21. A catadioptric optical system according to claims 19 or 20, wherein the at least one aspherical surface comprises an aspherical reflecting surface.

22. A catadioptric optical system according to any one of claims 1-21, wherein a second surface side numerical aperture of the catadioptric optical system is 0.6 or more.

23. A projection exposure apparatus comprising:

an illumination optical system for illuminating a mask on which a predetermined pattern is formed; and
a catadioptric optical system according to any one of claims 1-22, for projecting an image of the predetermined pattern onto a substrate.

24. A projection exposure apparatus according to claim 23, wherein the mask and the substrate are synchronously scanned with a speed ratio equal to the magnification of the catadioptric optical system.

25. A projection exposure apparatus according to claim 24. further comprising a slit-like exposure area.

26. A projection exposure apparatus according to any one of claims 23-25, wherein the illumination optical system provides a illumination light of a wavelength of 250nm or less.

27. A method of projection exposure comprising the steps of:

illuminating a mask on which a predetermined pattern is formed; and
projecting an image of the predetermined pattern onto a substrate using a catadioptric optical system according

to any one of claims 1-22.

28. A method according to claim 27, further comprising a step of synchronously scanning the mask and the substrate with a speed ratio equal to the magnification of the catadioptric optical system.

29. A catadioptric optical system having a single linear optical axis and operable to form intermediate and final images of a first plane surface, the final image being formed on a second plane surface substantially parallel to the first plane surface and the system including first and second reflectors, the first reflector reflecting light from the first plane surface to the second reflector and the second reflector reflecting light to the second plane surface.

FIG. 1

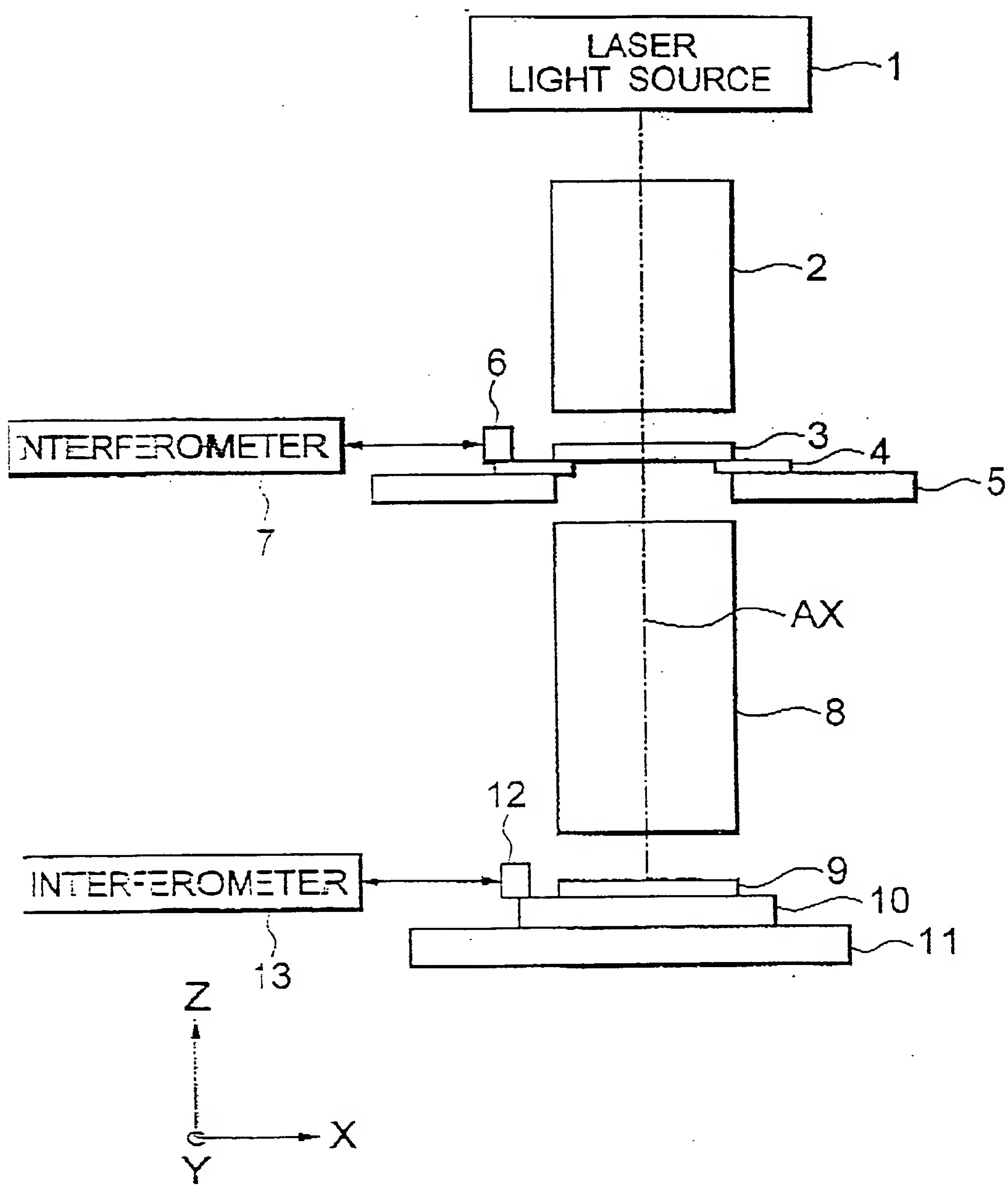

LASER
LIGHT SOURCE
1
2
6
INTERFEROMETER
3
4
5
7
AX
8
12
INTERFEROMETER
9
10
11
13
Z
X
Y

FIG. 2

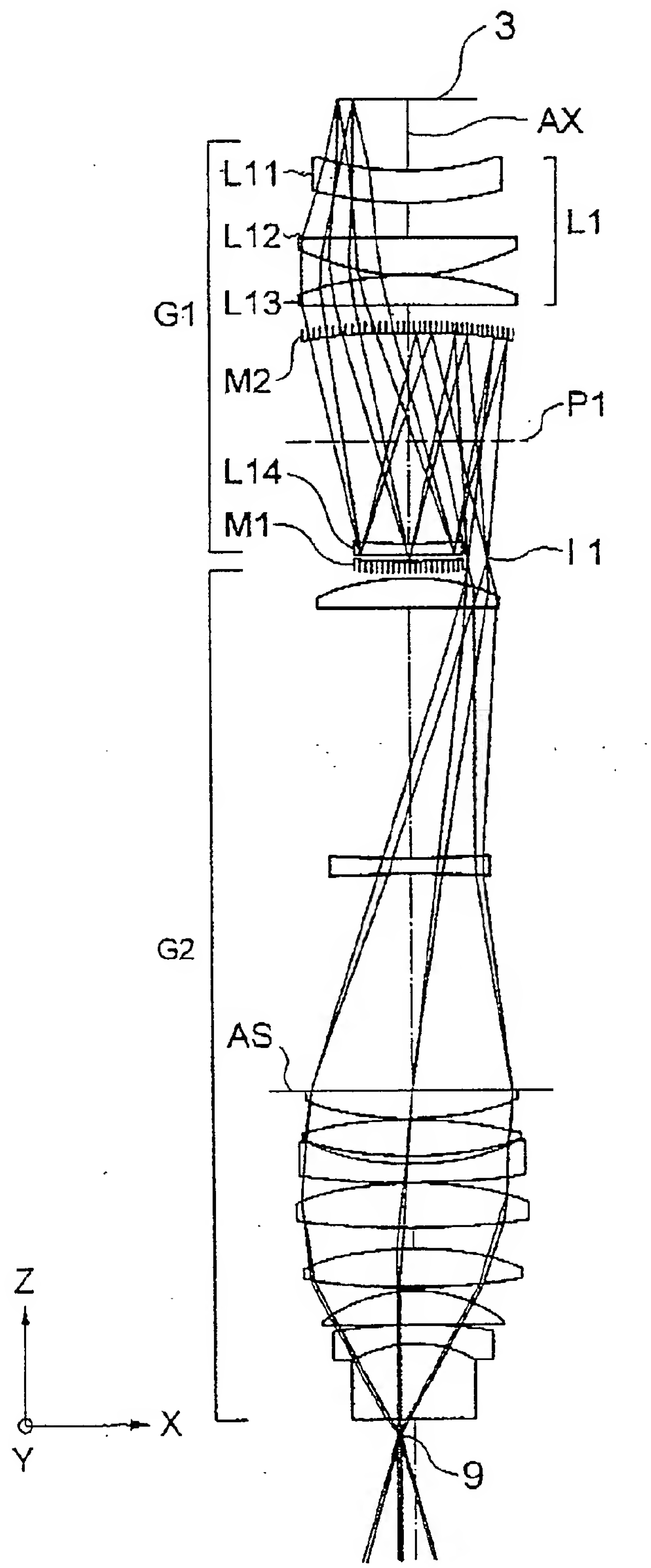
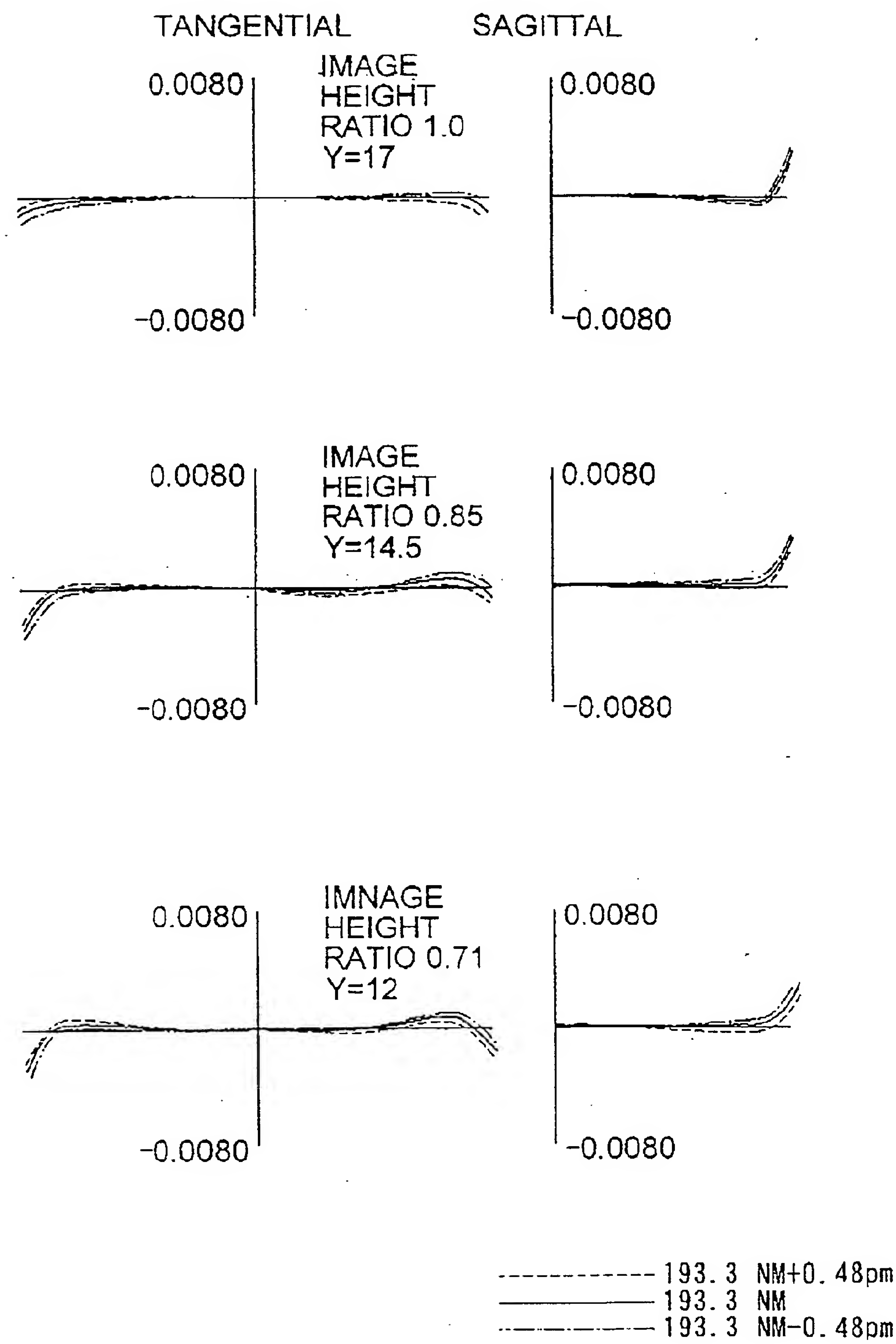


FIG. 3


TANGENTIAL
SAGITTAL
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0.0080
-0.0080
-0.0080
0.0080
IMAGE HEIGHT RATIO 0.85 Y=14.5
0.0080
-0.0080
-0.0080
0.0080
IMNAGE HEIGHT RATIO 0.71 Y=12
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-0.0080
-0.0080
193.3 NM+0.48pm
193.3 NM
193.3 NM-0.48pm

FIG. 4

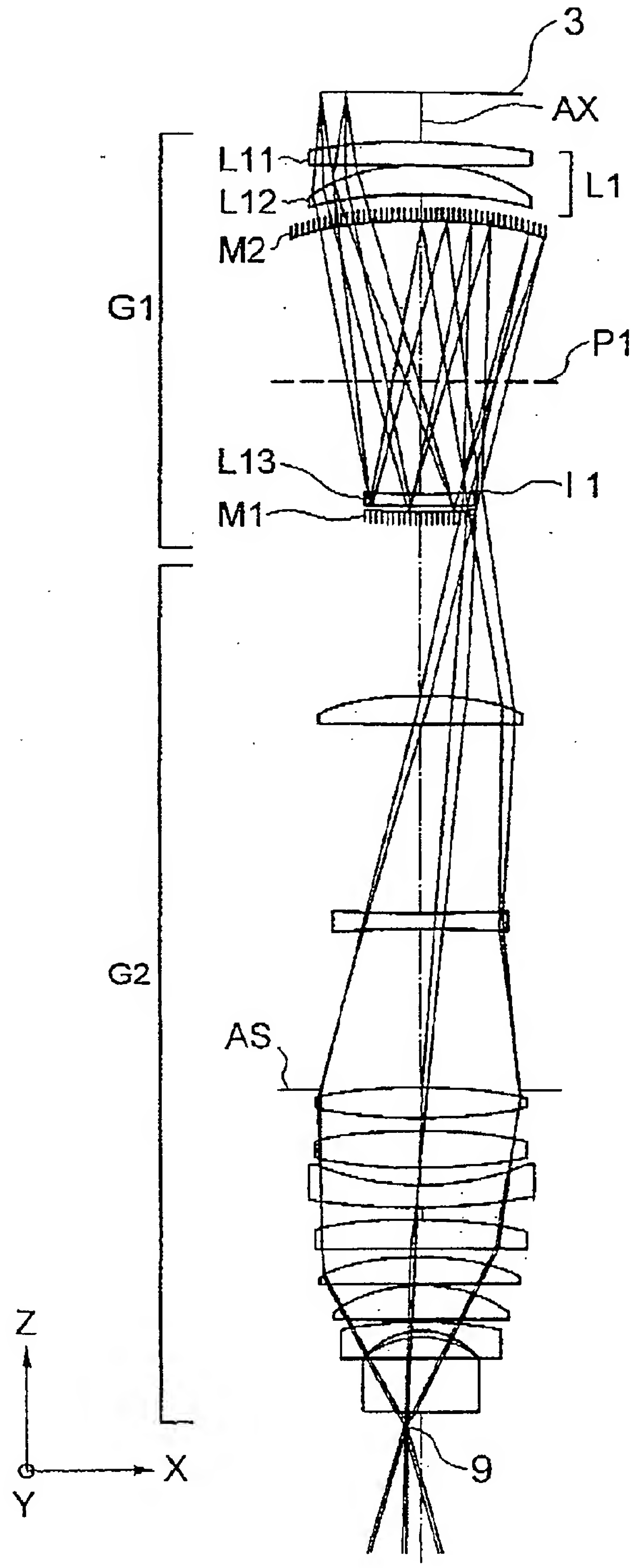
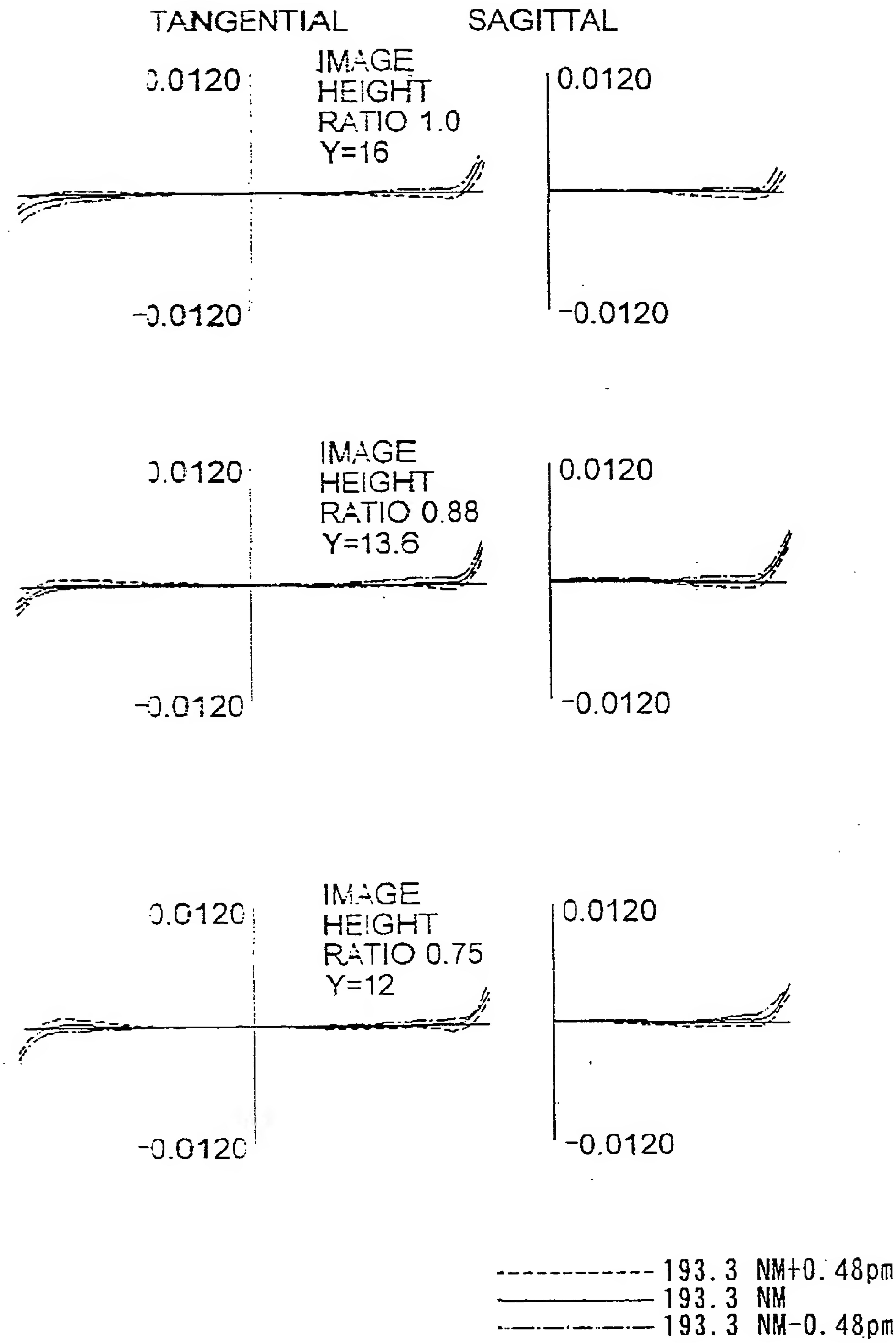


FIG. 5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SAGITTAL
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-0.0120
0.0120
-0.0120
IMAGE HEIGHT RATIO 0.88 Y=13.6
0.0120
-0.0120
0.0120
-0.0120
IMAGE HEIGHT RATIO 0.75 Y=12
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-0.0120
0.0120
-0.0120
193.3 NM+0.48pm
193.3 NM
193.3 NM-0.48pm

FIG. 6

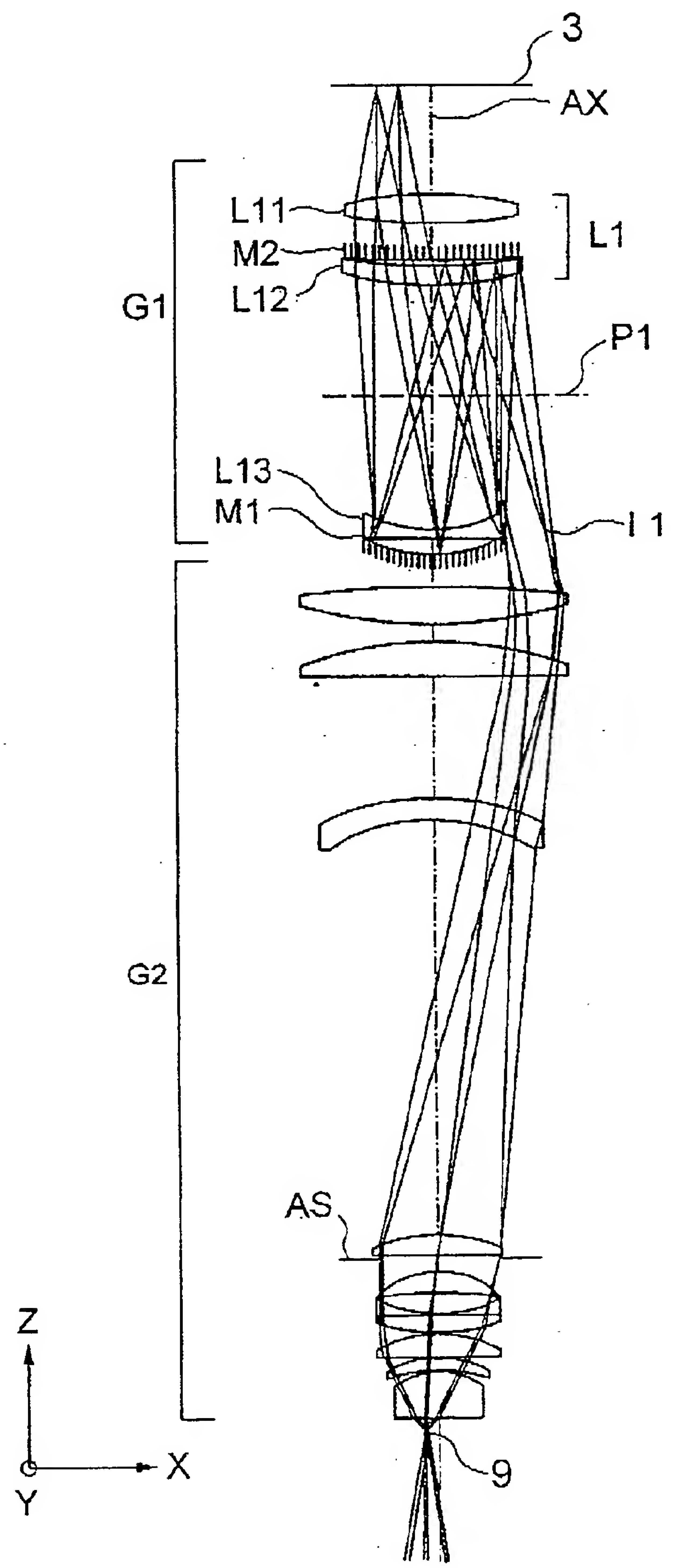
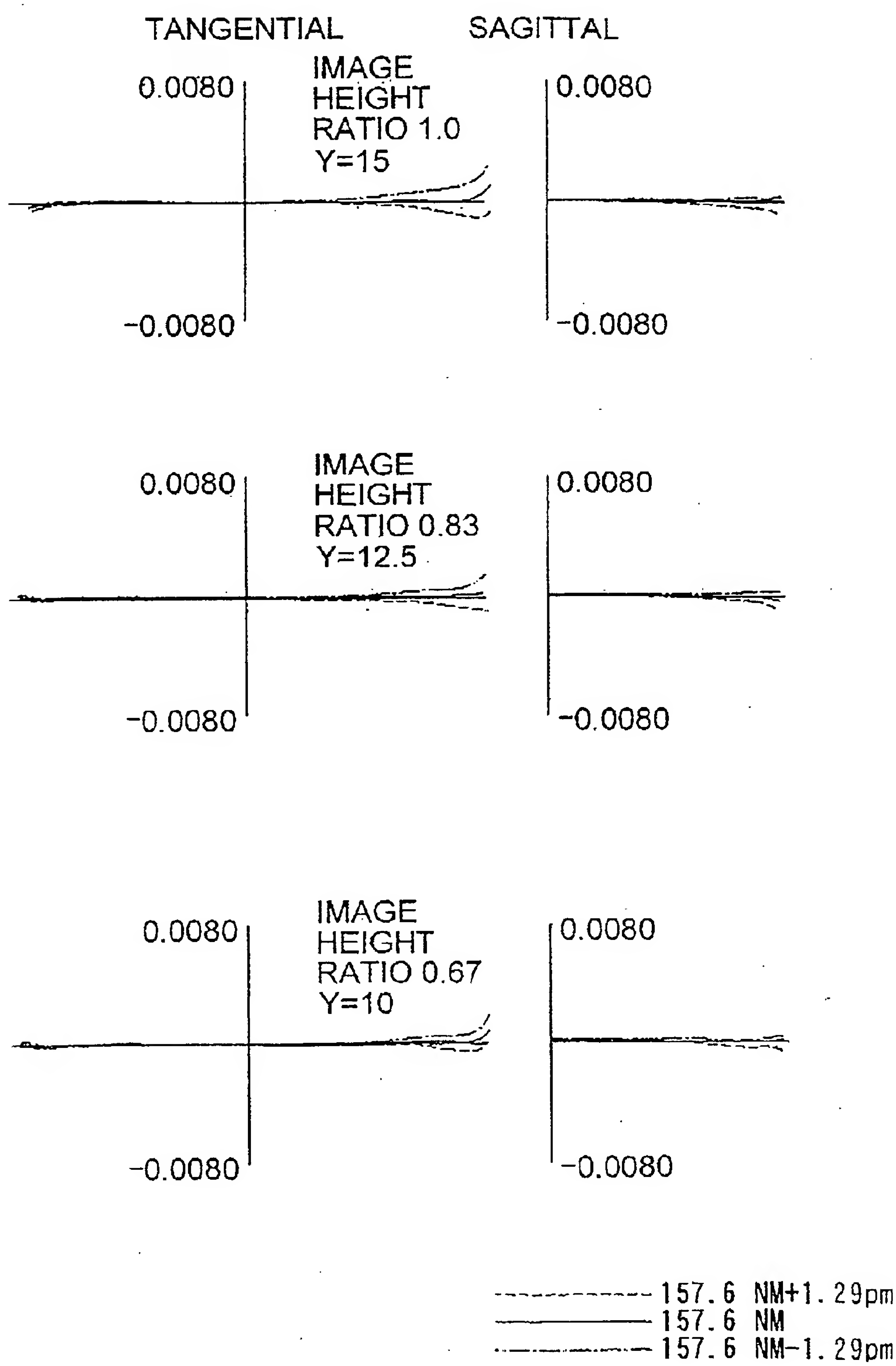


FIG. 7


TANGENTIAL
SAGITTAL
IMAGE HEIGHT RATIO 1.0 Y=15
0.0080
-0.0080
0.0080
-0.0080
IMAGE HEIGHT RATIO 0.83 Y=12.5
0.0080
-0.0080
0.0080
-0.0080
IMAGE HEIGHT RATIO 0.67 Y=10
0.0080
-0.0080
0.0080
-0.0080
157.6 NM+1.29pm
157.6 NM
157.6 NM-1.29pm